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Personal author: Hinkamp, Maddox Nelson Pieter.

Title: The problem of brittle fracture in metals.

Publication info: : Carnegie Institute of Technology, 1948.

Dissertation note: Research paper--Carnegie Institute of Technology,  
1948.

Bibliography note: Bibliography: leaves 34-36.

Subject: Metallurgy

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Carnegie Institute of Technology  
Pittsburgh, Pennsylvania.

THE PROBLEM OF BRITTLE FRACTURE IN METALS

*add ex*  
*W. N. Pieter Hinkamp*  
*W. N. Pieter Hinkamp*  
Lieut. Comdr., U.S.N.  
March, 1948

Department of Technology  
Pittsburgh, Pennsylvania

THE EFFECT OF TEMPERATURE ON THE  
RATE OF REACTION OF METALS

by J. H. PETERSON

Submitted in partial fulfillment of the requirements for the degree of  
Master of Science

March, 1962

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THE PROBLEM OF BRITTLE FRACTURE IN METALS

Attention has been focused in recent years on the all-important subject of brittle fracture. It is well to point out that if there were no controversies or discrepancies in the theories concerning brittle fracture, and if the state of knowledge was in a fairly satisfactory condition, the serious epidemic of failures in welded ship structures during World War II might never have happened. Much of the recent investigation and attention given to this subject stems from this one series of failures as added impetus towards the solution of one of the most outstanding questions in metallurgy.

This paper will be confined to the discussion of failure in the brittle manner only, and will not attempt to go into the field of ductile failure. It is the author's intention to present in concise form both the basic fundamentals and the most modern thought on this important subject, as well as some of the currently controversial points. A discussion of the modern theories concerning brittle fracture will be preceded by a brief analysis of the stress system acting at the moment of fracture. The effect of various factors on brittle fracture will be shown later.

There are four approaches to the problem of ~~the problem of~~ fracture, namely;-

- a. The study of the overall features, as evidenced by the

THE PROBLEM OF BRITISH TRADE IN AFRICA

Attention has been focused in recent years on the all-important subject of British trade. It is well to point out that if there were no controversies or discrepancies in the statistics concerning British trade, and if the state of knowledge was in a fairly satisfactory condition, the serious epidemic of failure in welded ship structures during World War II might never have happened. Most of the recent investigation and attention given to this subject stems from the one series of failures as added impetus towards the solution of one of the most outstanding problems in metallurgy.

This paper will be confined to the discussion of failure in the welded ship structure, and will not attempt to go into the field of general failure. It is an extensive literature in present times. Some of the main phenomena and the most recent progress in this literature will be given as some of the outstanding controversial points. A discussion of the modern theories concerning the failure of welded ship structures will be presented by a group of specialists of the subject, rather than the manner of treatment. The effect of various factors on welded structures will be shown later.

There are two main approaches to the problem of the welded ship structure.

1. The first approach is to the problem of the welded ship structure.

2. The second approach is to the problem of the welded ship structure.

stress system acting, in an effort to determine the conditions under which the fracture will occur.

b. The study of the metallurgical and chrystallographic structures to determine fracture characteristics.

c. The study of fractures from the level of atoms and cohesive energies.

d. The study from the standpoint of thermodynamics.

### Definitions:-

Before approaching the discussion of the stress system, definitions of brittle and ductile fracture should be made in the interests of clarity. In either case, a broad definition of fracture says that it is the termination of plastic flow in which there is a separation of surfaces. Ductile fracture occurs after a relatively large amount of plastic flow by the mechanism of shearing along the slip planes, which are generally at an angle of  $45^\circ$  to the axis along which the maximum normal stress is acting. The appearance of the fracture is characterized as fibrous, dull, and rough. Brittle fracture occurs after little or no plastic flow, occurs along cleavage planes within the metal c\hrystals, and is characterized by being normal to the axis along which the maximum normal stress is acting and is bright and c\hrystalline in appearance due to the many tiny facets produced when the c\hrystals are cleaved. Fractograph work by Zapffe on Bi, Zn, and Sb illustrate cleavage facets at high magnifications.

### Mechanism of Plastic Flow:-

- stress system acting, in an effort to determine the conditions under which the fracture will occur.
- b. The study of the metallurgical and crystallographic structures to determine fracture characteristics.
- c. The study of fractures from the level of atomic and cohesive energies.
- d. The study from the standpoint of thermodynamics.

Definitions:-

Before approaching the discussion of the stress system, definitions of brittle and ductile fracture should be made in the interests of clarity. In other cases, a broad definition of fracture says that it is the termination of plastic flow in which there is a separation of surfaces. Brittle fracture occurs after a relatively large amount of plastic flow by the mechanism of shearing along the slip planes, which are generally at an angle of 45° to the axis along which the maximum normal stress is acting. The appearance of the fracture is characterized as fibrous, dull, and rough. Brittle fracture occurs after little or no plastic flow, occurs along cleavage planes within the metal crystals, and is characterized by being normal to the axis along which the maximum normal stress is acting and is bright and crystalline in appearance due to the very fine facets produced upon the crystals and cleavage. Fracture work by brittle on B1, B2, and B3 fracture fracture levels at high resistance.

### Mechanism of Plastic Flow:-

Since by the above definitions it can be seen that fracture is inseparable from plastic flow, the mechanism of plastic flow should be briefly stated in order to fully understand the discussions relating to brittle fracture. Plastic flow occurs either by slipping or by twinning. Most of the experimental evidence is with single crystals in an effort to avoid many complicating factors. Slipping will cause a reorientation of areas within single crystals due to different slip directions and, of course, a reorientation of whole crystals. When grain boundaries are interposed between crystals, flow is interrupted by the conflicting slip directions and inhomogeneous strains are set up within the metal. This is the chief obstacle to the study of plastic flow in crystal aggregates. It has also been found that inclusions will reorient themselves to the slip direction and that fatigue or alternating stresses will cause slip bands to widen when plastic flow has been initiated. Crystal aggregates generally offer more resistance to flow than do single crystals. A further interesting concept is that of the viscosity or the behavior in the manner of an amorphous material in the grain boundaries. It appears that this is a transition region where the atoms for a few layers are not arranged in the crystalline structure of either grain. Slip bands also exhibit this amorphous behavior under strain.

### Analysis of the Stress System:-

As an introduction to the analysis of the stress system, it is useful to assume that the amount of deformation that can occur

Mechanism of Plastic Flow:

Since by the above definition it can be seen that fracture is inseparable from plastic flow, the mechanism of plastic flow should be briefly stated in order to fully understand the dislocations relating to plastic fracture. Plastic flow occurs either by slipping or by twinning. Most of the experimental evidence is with single crystals in an effort to avoid many complicating factors. Slipping will cause a reorientation of areas within single crystals due to different slip directions and, of course, a reorientation of whole crystals. When grain boundaries are intersected between crystals, flow is interrupted by the conflicting slip directions and lamellar structures are set up within the metal. This is the well known case to the study of plastic flow in crystal aggregates. It has also been found that inclusions will resist movement in the slip direction and that regions of alternating stresses will cause slip bands to widen when plastic flow has been initiated. Crystals aggregated generally offer more resistance to flow than do single crystals. A further interesting remark is that of the viscosity or the behavior in the manner of an amorphous material in the grain boundaries. It appears that this is a transition region where the atoms are a few layers and not arranged in the crystalline structure of either grain. Slip bands also exhibit this amorphous behavior under strain.

Analysis of Plastic Flow:

As an introduction to the analysis of the stress system, it is useful to assume that the amount of deformation that can occur

before flow or fracture sets in is determined by the relative values of the stresses required to cause slip, twinning, and cleavage. The recognized interrelation between plastic flow and brittle fracture brings up the added factor of the anisotropy introduced by the plastic strain. Non-perfect isotropy will invalidate the agreement with the following theory of combined stresses, but it is to be noted that <sup>at</sup> the small strains associated with brittle fracture the anisotropy is not great. Now, in single crystals, it is known that plastic flow will initiate when the stress, as resolved on the slip plane and in the slip direction, reaches a critical value (the critical shear stress). In polycrystalline metals, however, it is believed that plastic flow occurs when the shear strain energy reaches a critical value. This concept may be expressed by the following equation in which  $(\sigma_0)$  is the critical value and  $(\sigma_1)$ ,  $(\sigma_2)$ , and  $(\sigma_3)$  are the principal stresses along the principal axes (1), (2), and (3):

$$2 \sigma_0^2 = (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2$$

It is known that this equation is good for determining the beginning of plastic flow for most metals which will yield homogeneously. This equation of Von Mises has been substantiated for the cases of uniaxial and biaxial tension but not for the case of triaxial tension, due to the experimental difficulties and to some uncertainties surrounding the use of the notch bar impact test as a criterion. In the case of metals which yield inhomogeneously, the maximum shear stress law seems to be







obeyed in that yielding will occur when the maximum shear stress,

$$\frac{\sigma_1 - \sigma_3}{2}$$

reaches a critical value. A complication in this argument is introduced by Guest in which he proposes a theory that takes into account volumetric stresses. Experimental evidence in the form of adding hydrostatic pressure to the normal tensile stresses seems to validate his argument. This is but one of the many contradictory arguments surrounding this subject.

It should be noted here that the above discussion pertains to an idealized material and thus will only apply strictly to a small portion of the stress-strain curve for which values are known for the principal stresses. There is an extension of Von Mises' theory derived by Hencky, which states that the second invariants of the stress and strain tensors are functionally related. Ilyushin has extended this principle and shown case solutions. Prager advises caution in the use of these power laws, pointing out important variances between solutions and actual test plots. It is not within the scope of this paper to derive or prove this statement but merely to indicate the existence of this powerful tool. It can be said that the intensity of stress ( $\sigma$ ) defines a quantity whose square, except for a constant factor, is equal to the second invariant of the stress deviation. The intensity of strain ( $\epsilon$ ) is defined in a similar manner. The above values are sometimes also known as the significant stress ( $\bar{\sigma}$ ) and the significant strain ( $\bar{\epsilon}$ ) and are written as follows:

$$\bar{\sigma} = \frac{1}{\sqrt{2}} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]^{\frac{1}{2}}$$

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or prove this statement but merely to indicate the existence of

this powerful tool. It can be said that the intensity of stress

(1) defines a quantity whose square, except for a constant fac-

tor, is equal to the second invariant of the stress deviation. The

intensity of strain (2) is defined in a similar manner. The

above values are sometimes also known as the equivalent stress

(3) and the equivalent strain (4) and are written as follows:

$$\sigma = \frac{1}{\sqrt{2}} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]^{1/2}$$

$$\bar{e} = \sqrt{\frac{2}{3}} \left[ e_1^2 + e_2^2 + e_3^2 \right]^{\frac{1}{2}} \quad \text{where } e_1, e_2, e_3, \text{ are the strains along the principal axes.}$$

$$\bar{e} = D \bar{\sigma}, \text{ or } \bar{\sigma} = K \bar{e}^n \quad D, K, \text{ and } n, \text{ are constants.}$$

$$0 < n < 1$$

These equations give a generalized stress-strain relationship which does not depend on the type of stress.

There are two other important relationships usually assumed in problems of plastic flow. These are;

- a. The material is incompressible/ or the change in volume during plastic flow is zero.

$$e_1 + e_2 + e_3 = 0$$

- b. The principle shearing stresses and strains are proportional:

$$\frac{\sigma_1 - \sigma_2}{e_1 - e_2} = \frac{\sigma_2 - \sigma_3}{e_2 - e_3} = \frac{\sigma_3 - \sigma_1}{e_3 - e_1} \quad (\text{Hooke's Law})$$

With the generalized stress-strain relationships noted above, it is important to note that the significant stress and the significant strain are related by the proportionality factor (D). This relationship may take several convenient forms, not herein noted, for purposes of calculating specific problems.

#### Idealized Stress-Strain Diagram:-

The previous discussion leads to the stress-strain diagrams as determined for idealized materials and from which aid in further discussion of modern theories and effects of various factors on brittle fracture may be had. It is sufficient to merely

where  $\sigma_1, \sigma_2, \sigma_3$  are the strains along the principal axes.

$$\bar{\epsilon} = \sqrt{\frac{2}{3}} \left[ \epsilon_1^2 + \epsilon_2^2 + \epsilon_3^2 \right]^{\frac{1}{2}}$$

$D, K$ , and  $n$ , are constants.  
 $0 < n < 1$

$$\bar{\epsilon} = D \bar{\sigma}^n \quad \text{or} \quad \bar{\sigma} = K \bar{\epsilon}^{\frac{1}{n}}$$

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With the generalized stress-strain relationship noted above, it is important to note that the significant stress and the significant strain are related by the proportionality factor (D). This relationship can take several convenient forms, not herein noted, for purposes of calculating specific problems.

### Generalized Stress-Strain Diagram

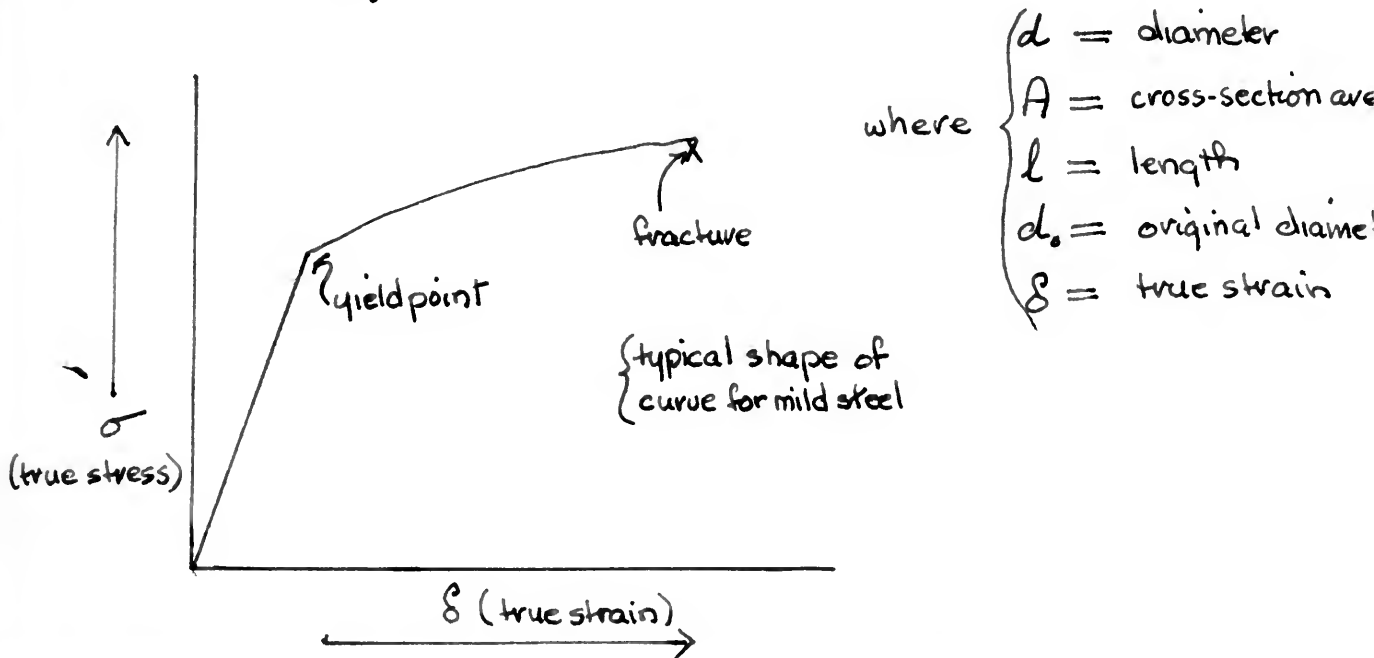
The previous discussion leads to the stress-strain diagrams as determined for idealized materials and from which it is further discussion of modern theories and effects of various factors on plastic behavior may be had. It is sufficient to merely

note the nominal stress-strain curve in which load/ original cross-section area ( tensile specimen ) is plotted against nominal strain. This type of curve gives rise to the familiar drop of the beam shape as experienced with steels. A modification of this early curve is the plot of true stress, load/ actual cross-section area at the instant of measurement, vs true strain, which is expressed as follows:

$$\text{Since } e_1 + e_2 + e_3 = 0$$

(or the volume remains constant)

$$Al = A_0 l_0 ; \quad \delta = \int_{l_0}^l \frac{dl}{l} = \ln \frac{l}{l_0} = \ln \frac{A_0}{A} = \ln \frac{d_0^2}{d^2} = 2 \ln \frac{d_0}{d}$$



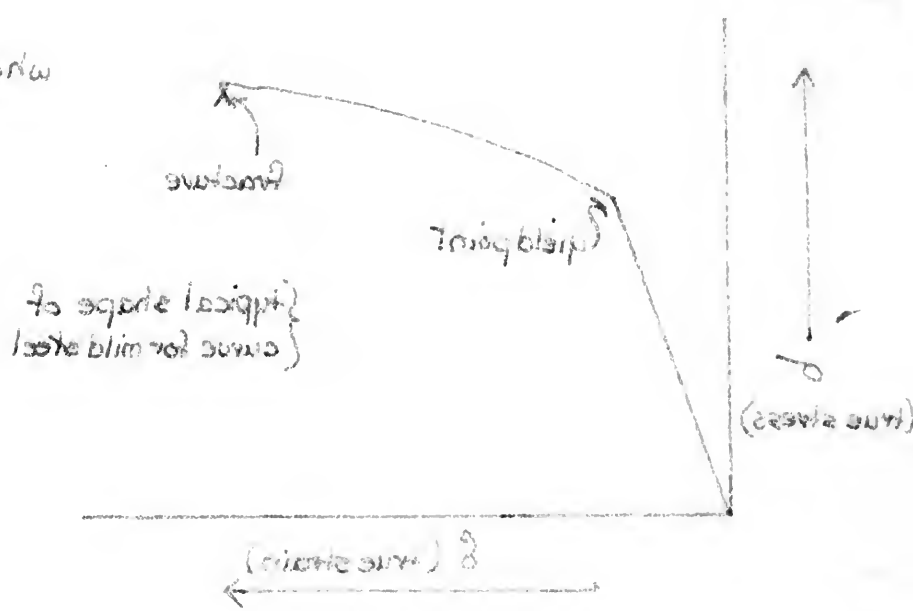
The above type of curve is known as the true stress-strain curve or more properly as a flow curve. The mathematical expressions previously noted generally apply well to the elastic region, but, where the problem of necking is encountered, the complex stress system and the non-uniform deformation cause the situation to be immeasurably complicated.

curve the actual stress-strain curve in which local, original cross-section area (original specimen) is plotted against nominal strain. This type of curve rises to the familiar drop of the stress-strain curve as a consequence of the localization of the strain. The only curve in the set of two curves, local, actual cross-section area at the instant of measurement, vs true strain, which is expressed as follows:

(or the volume remains constant)  $\epsilon_1 + \epsilon_2 + \epsilon_3 = 0$

$$A l = A_0 l_0 ; \delta = \int_{l_0}^l \frac{dl}{l} = \ln \frac{l}{l_0} = \ln \frac{A_0}{A} = \ln \frac{d_0^2}{d^2} = 2 \ln \frac{d_0}{d}$$

where  $\left\{ \begin{array}{l} d = \text{diameter} \\ A = \text{cross-section area} \\ l = \text{length} \\ d_0 = \text{original diameter} \\ l_0 = \text{true strain} \end{array} \right.$

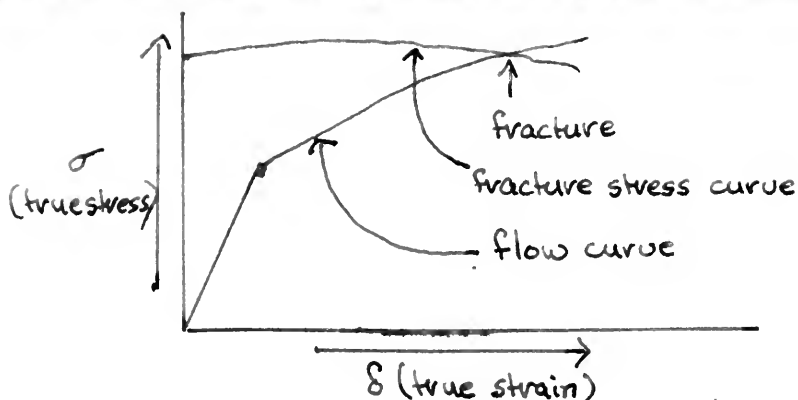


The above type of curve is known as the true stress-strain curve or true stress-strain curve. The mathematical expressions for the initial linear portion and the plastic region, but, these are not required to be considered, the complex stress-strain curve and the true stress-strain curve are shown in the following figure.

Ludwik's Theory:-

In beginning the discussion of the various theories, the introduction of the flow curve above leads to the discussion of Ludwik's theories and his postulation of a fictitious fracture curve. His work has been the basis of a great deal of research and thought on this matter particularly by Hollomon in recent years. The flow curve, per se, was originally recognized by Ludwik as possessing great possibilities for the interpretation of the mathematical statements. It is to be remembered that this curve applies to idealized material and thus requires a correction factor if it is to be used directly for any real material. Several people, notably Bridgeman and Davidenkov, have attempted to find suitable corrections to bring the plastic region of the curve down to meet the actual curve as determined from experiments. They have been more or less successful.

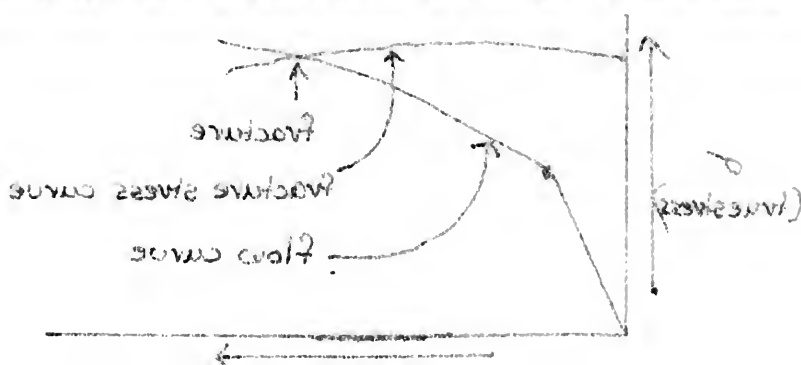
Ludwik conceived the idea of a fracture stress curve which is based upon saying that the fracture stress just before a metal fractures is greater than the stress required for plastic flow and that this fracture stress is dependent upon the prior deformation which the unbroken metal had gone through. It can be seen that a fracture stress and a flow curve must be determined under different external conditions. Ludwik postulates fracture as occurring when the flow curve intersects the fracture curve as seen;



Ludwik's Theory

In beginning the discussion of the various theories, the introduction of the flow curve above leads to the discussion of Ludwik's theories and his postulation of a fictitious flow curve. His work has been the basis of a great deal of research and thought on this matter particularly in relation to recent years. The flow curve, for us, was originally recognized by Ludwik as possessing great possibilities for the interpretation of the mathematical statements. It is to be remembered that this curve applies to idealized material and thus requires a correction factor if it is to be used directly for any real material. Several people, notably Bridgman and Castigliano, have attempted to find suitable corrections to bring the plastic region of the curve down to meet the actual curve as determined from experiments. They have been more or less successful.

Ludwik conceived the idea of a fracture stress curve which is based upon the fact that the fracture stress just before a metal fractures is greater than the stress required for plastic flow and that this fracture stress is dependent upon the prior deformation which the material metal had gone through. It can be seen that a fracture stress and a flow curve must be determined under different external conditions. Ludwik postulated fracture as occurring when the flow curve intersects the fracture curve as seen;





The greatest justification for the use of a fracture curve, although it is a fictitious concept, is its inherent ability to explain conveniently many different effects on the fracture of metals. The various effects are noted as raising or lowering the flow curve, the fracture curve, or both.

Hollomon has pointed out that there may be a great effect due to anisotropy of the metal structure as caused by prior deformation. This point has not been sufficiently investigated. Fracture stress analyses made with notched tensile bars have been recently made by McAdam, in which it is assumed that fracture begins in the center of the bars. Results can be interpreted as applying triaxially in which fracture stress is shown to increase with increasing triaxiality. This is further corroborated by experiments performed by Sachs. In this case, the fracture curve rises, but, at the same time, the flow curve is also rising at a greater rate, which essentially reduces the strain needed for fracture although the stress is raised. This serves as one illustration of the use of flow and fracture curves. There has been a great deal of ~~criticism~~ criticism of these curves, but it is desired to emphasize that they make no attempt to explain the whole phenomenon of fracture but serve as a useful tool and as such should not be overlooked. It should be further emphasized that the fracture curve is a purely fictitious concept.

Sternberg has replaced the linear expression of Hooke's law, previously noted, with a general second order approximation which assumes non-linearity within the elastic range. His results show definite second order effects, in particular, where such

The present position in the use of a fracture curve, although it is a traditional concept, is less important ability to explain conveniently any different effects on the fracture of metals. The various effects are noted as relating to increasing the flow curve, the fracture curve, or both.

Attention has pointed out that there may be a great effect due to anisotropy of the metal structure as caused by prior deformation. This point has not been sufficiently investigated. Fracture stress analysis made with notched tensile bars have been recently made by Adams, in which it is assumed that fracture begins in the center of the bars. Results can be interpreted as applying preferably in which fracture stress is shown to increase with increasing strain rate. This is further supported by experiments performed by Adams. In this case, the fracture curve rises, but, at the same time, the flow curve is also rising at a greater rate, which essentially reduces the strain needed for fracture although the stress is raised. This curve is one illustration of the use of flow and fracture curves. There has been a great deal of extensive criticism of these curves, but it is difficult to summarize that they make no attempt to explain the whole phenomenon of fracture but serve as a useful tool and as such should not be overlooked. It should be further emphasized that the fracture curve is a purely descriptive concept.

Although less rigidly the linear relationship of Hooke's law, practically correct, with a constant second order approximation with constant non-linearly elastic range. The results show different behavior under stress. In particular, where such

materials as cast iron and concrete are concerned. Sternberg's work is based on Voigt's five parameter theory in which the classical expression of Hooke's law is the limiting case. It is believed that this theory of non-linearity within the elastic *range* may well explain the baffling behavior of cast iron according to conventional solutions.

#### Micro-Crack Theory:-

Strength, as applied to metals has a very definite meaning:

- a. Resistance to flow.
- b. Resistance to fracture.

The fracture strength is very much more structure sensitive than the flow strength, which is an important factor when considering the capacity to deform and to absorb energy before fracture. Closely related to the above is the structure sensitivity of the cohesive strength in which it is known that minute imperfections or even a precipitate will induce brittle behavior. This introduces the well known micro-crack theory.

One of the most intriguing aspects of the whole problem of fracture and the one which may hold the key to the ultimate explanation of the phenomenon is the effort to explain why the actual strength of metals is so low when by calculations based on the cohesive strength between atoms and lattice planes the fracture strength should be from one hundred to one thousand times greater. In a general way, the micro-crack theory attempts to explain this great discrepancy by saying that there are tiny cracks within the crystal structure of the metal which act as stress raisers and thus concentrate the stress under conditions

materials as most iron and concrete are concerned. Stenberg's work is based on Volz's five parameter theory in which the classical expression of Hook's law is the limiting case. It is believed that this theory of non-linearly elastic materials may well explain the yielding behavior of cast iron according to conventional solutions.

#### Micro-Grain Theory

Strength, as applied to metals has a very definite meaning

a. Resistance to flow.

b. Resistance to fracture.

The fracture strength is very much more structure sensitive than the flow strength, which is an important factor when considering the capacity to deform and to absorb energy before fracture. Closely related to the above is the stress-strain sensitivity of the cohesive strength in which it is known that minute imperfections or even a dislocation will initiate brittle behavior. This introduces the well known stress-concentration theory.

One of the most interesting aspects of the whole problem of fracture and the one which may hold the key to the ultimate explanation of the phenomenon is the effort to explain why the actual strength of metals is so low when calculations based on the cohesive strength between atoms and lattice planes the theoretical strength of metals is so high and is based on the energy required to pull one atom out of its position in the lattice. In a general way, the micro-grain theory attempts to explain this great discrepancy by saying that there are tiny voids which are created at the surface of the metal which act as stress raisers and are concentrated under conditions

of restraint to the point that the fracture strength, in a highly localized region, is exceeded and fracture initiates at a stress very much lower than that predicted by the cohesive strength of the atomic bonds.

Griffith has worked on this problem from an interesting point of view and his ideas have formed the basis of a great deal of recent work. His fundamental concept is that, in a solid, the boundary surfaces possess a surface tension which implies the existence of a corresponding amount of potential energy, and if, due to stress, a crack is formed or an already existing one is extended, an amount of energy proportional to the area of the new surface formed must be added and this must be done without any increase in the total potential energy of the whole system. This new energy must come from the decrease in the potential caused by the spread of the crack. These two energies must be balanced for the crack to propagate. Based on this reasoning, Griffith derived an expression for the fracture stress: ( $\sigma_f$ ):-

$$\sigma_f = \sqrt{\frac{2SE}{C\pi}}$$

Where---

{	S	is the surface energy/ unit area
	E	" " modulus of elasticity
	$\pi r$	" length of the crack
	C	" constant

There are three assumptions that should be mentioned;

1. The material is perfectly elastic.
2. The distribution of cracks is such

of resistance to the point that the fracture strength, in a highly localized region, is exceeded and fracture initiated at a stress very much lower than that predicted by the cohesive strength of the atomic bonds.

Griffith has worked on this problem from an interesting point of view and his ideas have formed the basis of a great deal of recent work. His fundamental concept is that, in a solid, the boundary surfaces possess a surface tension which implies the existence of a corresponding amount of potential energy, and if, due to stress, a crack is formed or an already existing one is extended, an amount of energy proportional to the area of the new surface formed must be added and this must be done without any increase in the total potential energy of the whole system. This new energy must come from the decrease in the potential caused by the spread of the crack. These two energies must be balanced for the crack to propagate. Based on his reasoning, Griffith derived an expression for the fracture stress:

$$\sigma_f = \sqrt{\frac{2E\gamma}{\pi a}}$$

where

$$\left. \begin{array}{l} \sigma_f \text{ is the surface energy / unit area} \\ E \text{ is the modulus of elasticity} \\ \pi a \text{ is the length of the crack} \\ \gamma \text{ is a constant} \end{array} \right\}$$

There are three assumptions that should be mentioned:

1. The material is perfectly elastic.
2. The distribution of stress is such

that there is no mutual interference.

3. The state of the stress is two-dimensional.

In using the above equation it is further assumed that the cracks are plane discs, perpendicular to the axis of the specimen.

Griffith carried out his experiments using glass rods of varying thicknesses. With extremely thin glass rods he was able to attain a strength of about one fourth the theoretical but when he used the slightly larger rods his strength fell off rapidly. This brings up the size effect which will be discussed later. His ideas relative to the effect of defects in causing fracture can, however, be applied to metals. Assuming the presence of the defects, when a metal is strained in the plastic region, the defects will reorient themselves if they are plate-like so that less strain energy will be released by their propagation and the stress at which fracture will occur will be raised. Another concept is that, as the defect is rotated away from being perpendicular to the axis of stress, the stress concentration at the end of the defect becomes less and the defect then has proportionally less effect on lowering the fracture stress.

Zener theorizes that the grain boundaries of metals are perfectly homogeneous but have less resistance to slip than the interior of the grain. When a strain is applied, a stress concentration is set up in the grain boundaries due to the inhomogeneity of the strain and he then believes that this may lead to sufficient internal energy to propagate cracks. It should be remembered that the defect causing fracture is the one producing the largest stress concentration.



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There are criticisms of the micro-crack theory which should be noted;

1. It must be assumed that the weaknesses occur in a fairly regular fashion.
2. If stress concentrations are involved in the fracture process they could not alone account for the low shearing stress values for slip.

### Statistical Theory:-

There are several observed facts which are fairly well known and which have led to additional research, some of it along statistical lines. With steels, the component of the metallurgical structure that controls the fracture stress is the size, shape, and distribution of the carbide particles. When the carbides are spheroidized, for example, the fracture stress is considerably raised, due to the lowering of the stress concentrations. It is also known that the fracture stress depends greatly upon the prior deformation or strain and that the shape of the fracture curve varies widely.

The size effect, as previously noted, in the work of Griffith, has a very important bearing on the fracture strength. The observed facts are that, as the specimen size is increased, brittle fracture will occur with less unit stress and with less work per unit volume required to propagate the crack. These facts led to the statistical analysis by Ruark of crack distribution and density as well as the study of the number, type, and distribution of inclusions per square inch of etched surface on steel.

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tion of inclusions per square inch of etched surface on steel.

An interesting comment in Ruark's work expresses the belief that the influence of the general pattern of stress raisers is the most potent factor available for explaining otherwise incomprehensible variations in the behavior of different heats of steel. Davidenkov, in working with plain carbon steels, found that a threefold increase in all dimensions does not give a three-fold increase in the energy required to break under impact but rather only about half the expected value. He further found a greater tendency towards brittle fracture with large specimens. He showed that the size effect is not connected with the velocity of testing and thus he based his experiments on the notch bend test rather than the impact test. Davidenkov stated that statistical theory is the only way to explain the size effect and he based his work on the statistical mathematics of Weibull, who established the dependence of strength on the volume of the specimen.

Weibull pioneered the statistical approach to the problem of fracture and all later work is based on his fundamentals. Briefly, statistical theory as related to brittle fracture says that brittle failure is determined not by the value of the average stress but by the value of the local stress at the locus where the most dangerous structural defect or flaw is located. The specimen is considered to be a set of volume elements of varying strengths connected in series, the distribution of strength values along the series being according to probability (random distribution). The larger the whole piece, the weaker is the weakest element or rather the probability of having an extreme value of strength is greater when a large number of elements

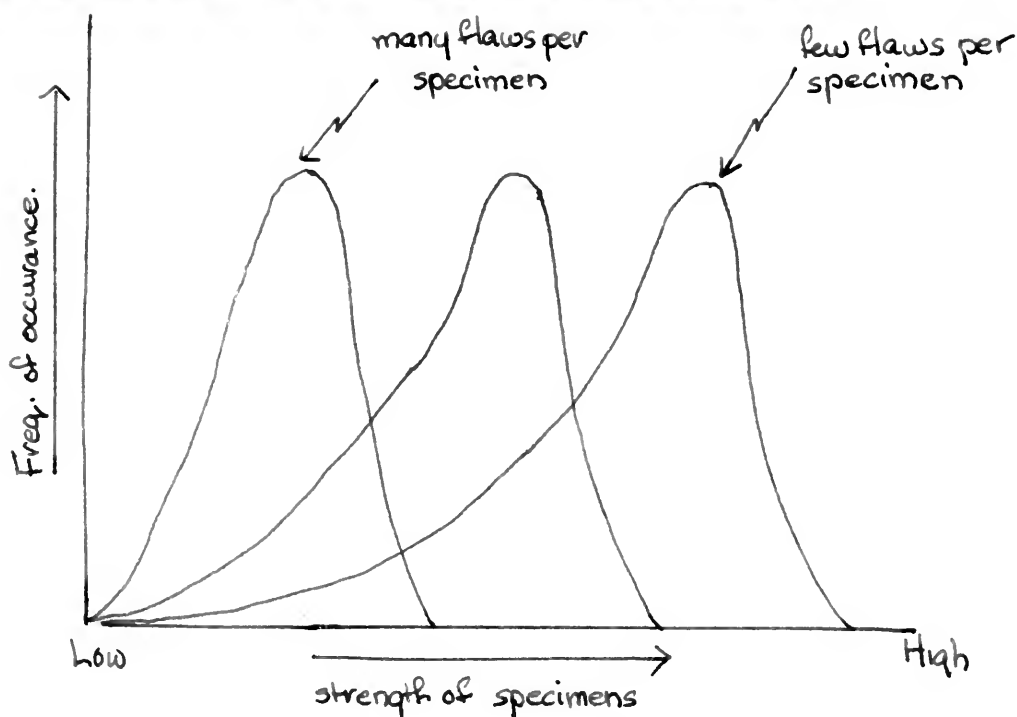
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is used. Weibull noted that the dispersion in measured tensile strengths required a distribution function to measure it. The statistical problem is the one of distribution of the smallest value in samples of size  $(n)$  drawn from a population having some probability density function,  $f(x)$ . The probability of rupture  $(S)$  at any given distribution of stresses  $(\sigma)$  over a volume  $(V)$  is:

$$\log(1-S) = - \int_V n(\sigma) dv$$

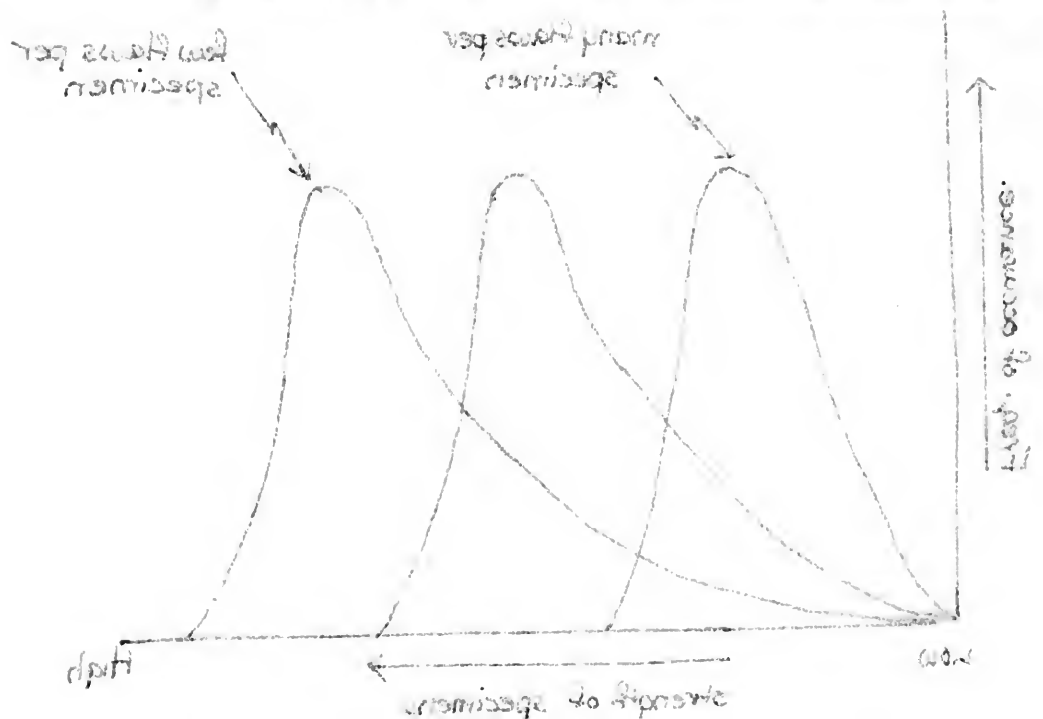
where  $n(\sigma)$  is a characteristic function of each material. This allows for a calculation of the effect of volume on the tensile strength. It is to be noted that the flaws are assumed to be randomly distributed through the specimen and that each flaw is independent of the other. This theory is good for explaining brittle fracture only, and even then makes no effort to explain the entire phenomenon. The following curve shows qualitatively how the strength of the specimen varies with the number of flaws per specimen and their frequency of occurrence;



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$$\log(1 - P) = - \int_0^\infty n f(\sigma) d\sigma$$

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Fisher and Holloman have pursued this statistical trend in an effort to show the effects of strain rate, size, and structure. " The fracture of a real material can be investigated theoretically only by idealizing both the structure of the material and the method of fracture. The idealized model selected for analysis can be justified and accepted as a valid representation if the results of the theoretical analysis are in agreement with the observed facts....."

The above quotation characterizes this work, which again is based on Weibull's fundamental statistical analysis. Their assumptions are:

1. The structure is an elastic solid containing many cracks.
2. The cracks are thin and disc-like with elliptical cross sections.
3. The cracks are orientated at random.
4. The cracks are separated on the average widely enough so that there is negligible amount of interference of the regions of local distortion which surround each crack under elastic strain.

The mathematics will not be presented within this paper but it is sufficient to point out that the normal laws of probability and statistical analysis were followed.

The results of these very interesting statistical analyses into brittle fracture give means to calculate the effect of specimen size on the fracture stress, predict the scatter of



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The results of these very interesting statistical analyses into brittle fracture give means to calculate the effect of applied stress on the fracture process, predict the behavior of



fracture stress measurements ( shows when chance causes are operating) and calculate the effects of combined stress and plastic deformation. It is to be remembered that this analysis is based on the assumption that fracture in solid materials is caused by the presence of randomly oriented defects having the properties of cracks. Agreement with known facts, and in particular with the previous work of Griffith is very good. When there is a compressive pre-strain the fracture stress is observed to increase. this is in disagreement with Hollomon and Fisher's work and seriously endangers the micro-crack theory.

Thermodynamic or Energy Theory:-

A number of years ago, ~~Fath~~ Fürth advanced a theory relating the tensile strength of metals to the melting of crystals but there were several serious objections to his work, namely that there were no provisions for the effect of plastic flow, alloying elements, or heat treatment. Another objection was that his theory was impossible to check precisely since it applied only to isotropic bodies that remained completely elastic up to the point of fracture. It is highly doubtful that this is the case since all fractured surfaces show evidence of some plastic flow. Saibel has taken the fundamental idea of relating fracture to the melting phenomenon but he has developed a different relationship that eliminates the major objections to Fürth's work.

Saibel's thermodynamic approach contains three basic

fracture stress measurements (shows when chance causes are operating) and calculate the effects of combined stress and plastic deformation. It is to be remembered that this analysis is based on the assumption that fracture in solid materials is caused by the presence of randomly oriented defects having the properties of cracks. A treatment with known facts, and in particular with the previous work of Griffith is very good. When there is a compressive pre-stress in the fracture stress is observed to increase. This is in disagreement with Halloran and Wipac's work and seriously endangers the micro-crack theory.

#### Thermodynamic or Energy Theory

A number of years ago, I think I covered a theory relating to the local energy of atoms in the vicinity of dislocations but there were several serious objections to his work, namely that there were no provisions for the effect of plastic flow, allowing dislocations, or their treatment. Another objection was that his theory was impossible to check because it applied only to isotropic bodies that remained completely elastic up to the point of fracture. It is highly doubtful that this is the case since all fractured surfaces show evidence of some plastic flow. Indeed, I think the fundamental idea of relating fracture to the local phenomenon has been developed a different relationship that eliminates the major objections to Griffith's work.

Griffith's thermodynamic approach contains three basic

assumptions:-

1. All of the strain energy is available for the abolition of cohesive strength.
2. The heat of fusion is uniformly partitioned throughout the volume occupied by the substance.
3. The quantity of energy required for the abolition of cohesive strength is equal to the fractional change in specific volume as the material passes from the solid state to the liquid, multiplied by the heat of fusion.

Saibel's critical condition is expressed as follows:-

$$u = J L_m \frac{\Delta V}{V}$$

where:-

- $u$  is the strain, energy / unit volume.
- $L_m$  is the latent heat of melting / mol
- $\Delta V$  is the change in volume of one mol of the substance on passing from the solid to the liquid state.
- $V$  is the molecular volume in the solid state at the melting point.
- $J$  is the conversion factor to make the units consistent.

It is further noted that the fracture tests are not carried out slowly so there is no leakage of energy in the form of heat out of the specimen and that the change in volume on melting is due to the formation of " holes " as based on the Eyring model of

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Gibbs's critical condition is expressed as follows:-

$$u = T \left[ \frac{\Delta V}{V} \right]$$

where:-

$u$  is the strain energy / unit volume.

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the liquid state.

In using the theory, the following form of the energy equation is useful since it can be considered that, after plastic flow has occurred, the elastic energy is negligible, as compared with the energy of distortion, and

$$u = \int \bar{\sigma} d\bar{\epsilon}$$

where ( $\bar{\sigma}$ ) and ( $\bar{\epsilon}$ ) are the significant stress and significant strain. Further, the relation previously noted

$$\bar{\sigma} = k\bar{\epsilon}^n$$

gives a convenient means of actually calculating desired values.

Making use of the above noted expressions, Saibel performs calculations for the case of pure brittle fracture and fracture preceded by plastic flow. The fracture stresses ( $\sigma_f$ ) as calculated show good agreement with actual values and Saibel states that the agreement is good enough for a purely brittle case and thus no need exists for the micro-crack theory. The discrepancies are due to inaccurate thermodynamic data to a large extent. It is also desired to point out that there is controversy surrounding the important point of whether purely brittle fracture is preceded by some plastic flow. Saibel says that there is always some plastic flow prior to fracture, even if it is only a few atom layers in extent.

#### The Relaxation Phenomenon:-

It can now be seen that there has been a great difference of opinion and ideas surrounding this problem of brittle fracture. It is a well known fact, however, that the progress of scientific knowledge is measured by the controversial nature of argu-

In using the theory, the following form of the energy equation is needed since it can be considered that, after plastic flow has occurred, the elastic energy is negligible, as compared with the energy of distortion, and

$$u = \frac{1}{2} \sigma \epsilon$$

where  $(\sigma)$  and  $(\epsilon)$  are the significant stress and significant strain. Further, the relation previously noted

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gives a convenient means of actually calculating desired values. Making use of the above noted expressions, Eshelby performs calculations for the case of pure brittle fracture and fracture

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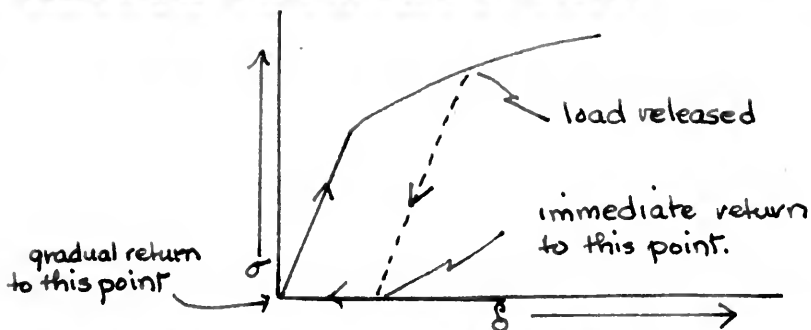
some plastic flow prior to fracture, even if it is only a few atomic layers in extent.

### The Relation Between:

It can now be seen that there is a great difference of opinion and ideas surrounding this problem of brittle fracture. It is a well known fact, however, that the process of brittle fracture is surrounded by the controversy of signs

ments until conclusive and indisputable evidence is presented and accepted. As a further measure of the unsettled state of affairs in this field, Zener has attacked fracture from the standpoint of the relaxation phenomenon, which is in striking contrast to previous ideas.

Since relaxation is tied up with anelasticity, the recovery of plastic deformation with time, a true stress-strain diagram will illustrate the over-all effects:-

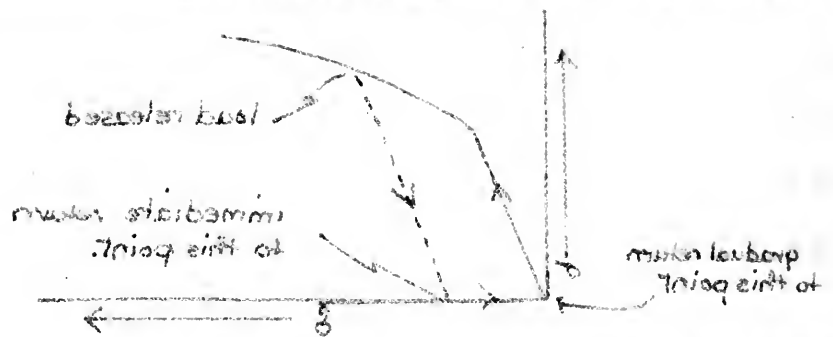


It is to be remembered that elevating the temperature, even slightly, for most metals will eliminate anelastic effects and allow recovery after the stress is removed. It has been believed for a long time that the anelastic effects were due to a region within the metal behaving in a viscous manner. Grain boundaries and slip bands are the regions which will obey the laws of viscous behavior. The following sketches serve to show in principle what happens within the crystal. Assume that the heavy lines represent a viscous slip band within a lattice:

( see next page for sketches )

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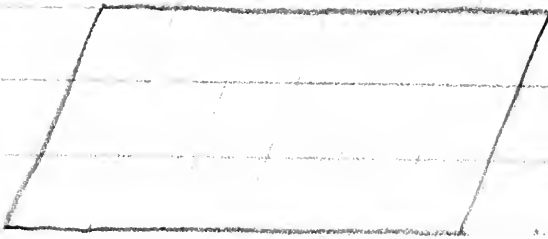
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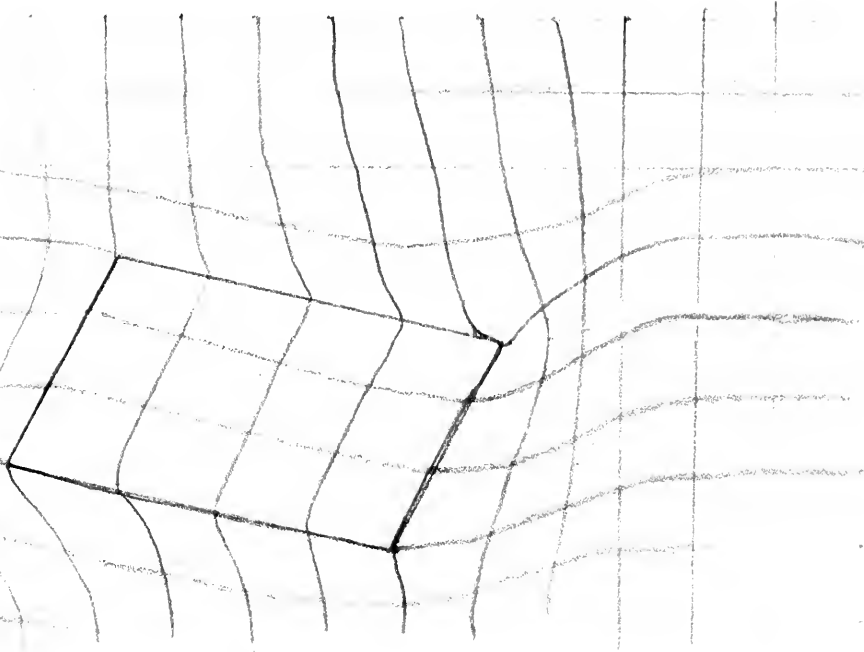
It is to be understood that relaxation is a phenomenon, even slightly, for most metals will exhibit anelastic effects and allow recovery after the stress is removed. It has been believed for a long time that the anelastic effects were due to a reaction within the metal behaving in a plastic manner. (This is understood and slip bands are the regions where the lines of dislocation move. The following diagram serves to show in simple terms the nature of the phenomenon. Assume that the metal is represented by a series of parallel lines within a lattice:

(continued on next page)





Load, no relaxation.



Load removed, no relaxation..



load, no relaxation.



load removed, no relaxation.

Note that the stress concentrations at the corners can be very heavy and can only be removed by relaxation or fracture. Zener has used this phenomenon of relaxation to develop a theory which will allow a prediction of the fracture stress.

There is considerable doubt as to whether grain boundaries should be considered at all in attempting to work out a theory of brittle fracture. This is another instance where the controversy is intense and far from being resolved.

#### Mechanical Testing:-

Since the proof of any theory lies in the effectiveness of its predictions, some mention should be made of the means by which the predictions are tested and their relative merits. Essentially there are four tests:-

1. Simple tension test.
2. Notched tension test.
3. Notch bend test.
4. Notch impact test.

There is also the torsion test which is normally not applied to a study of brittle fracture.

The simple tension test, when used for data on brittle behavior, hardly needs any comment, being familiar in a more or less degree to all metallurgists. It may be noted, in passing, that the complex stress system caused by necking down is, in general, a negligible factor in brittle fracture but extremely important in analysing ductile behavior.

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### Mechanical Testing:-

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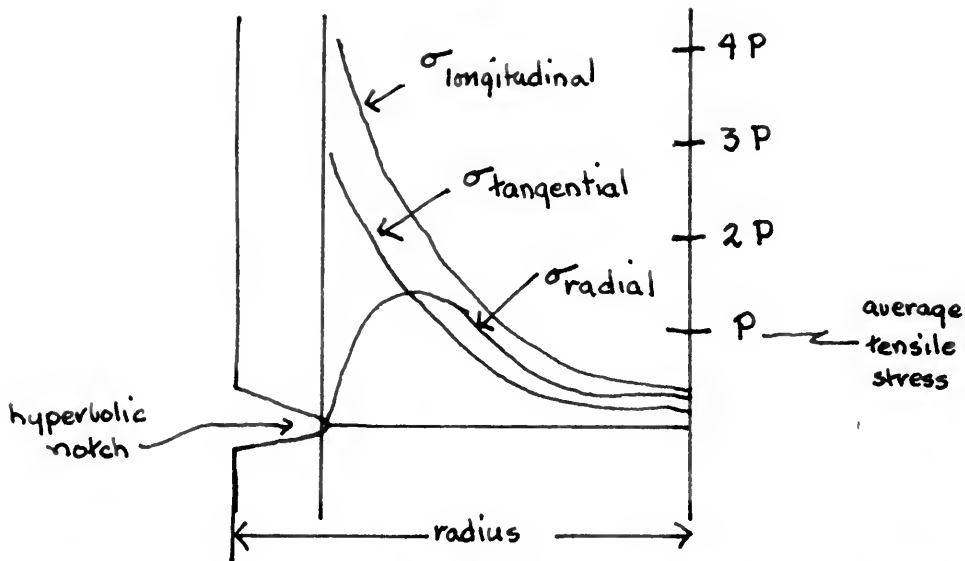
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When the tensile (normal) specimen is notched, a new and very different situation applies. The effect of the notch is two-fold. First, it serves to reduce the cross-section area and, second, it acts as a stress concentrator. There is some controversy over the effectiveness of this type of tensile specimen. The greatest difficulty in the proper interpretation of the data, due to the factors of size effect, stress concentration, and lack of knowledge of the stress state.

Since notches are being used more frequently, a brief explanation of their effect will be useful. Notches are introduced for the purpose of setting up a controlled condition of stress concentration and also to attempt to set up a condition of multi-axial stresses in an effort to study fracture and fracture stress under multi-axial loading. Gensamer has done a great deal of work in attempting to resolve the difficulties and to correlate the data (notched) with each other and also with the simple tensile test. Neuber has developed a series of nomograms which give the stress concentration factors for the elastic state. It is to be noted that the severity of the notch is most important., a sharper notch requiring less energy to initiate a fracture. A stress concentration curve will show the magnitudes of the stresses at the notch. Note that the amplitude falls off rapidly and that the stress level away from the vicinity of the notch is less than if there were no notch. Also note the relative amplitudes of the multi-axial stresses.

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The problem of correlation of the various tests has progressed to a satisfactory state generally and the choice of test will depend upon the relative ability to show desired characteristics.

The notch bend and the notch impact tests are often used when testing brittle behavior, especially the notch impact test. The notch impact test allows for a fast rate of loading not possible in the normal tension test. As will be seen later, this may be an important factor. Due to the extensive work on correlation, confidence in notched tests has increased somewhat.

#### Influence of Various Factors:-

From time to time, mention has been made of the fact that fracture strength varies according to the influence of various effects. The influence of size on the specimen has already been discussed with the development of statistical approach by Weibull. In an engineering sense, the effects of various factors can be far more important than the basic theory. Unfortunately the over-all influence of size effect, temperature, strain rate, and other factors can not be well established until the precise





mechanism of brittle fracture is fully understood. Despite the latter drawback, a brief discussion of each factor should be made, along with an explanation of the phenomenon when known.

#### Size Effect;-

Size effect, although mentioned previously, is known to be the lowering of the fracture stress and the energy required to propagate the fracture, when the size of the specimen is increased. This is the most apparent with steel and both Davidenkov and Fisher and Hollomon have used Weibull's statistical methods in an attempt to find a suitable explanation of this phenomenon. Size effect is, by its very nature, closely allied with the distribution of particles, such as carbides, and their shape within the structure of the metal. This is extremely important when considering the design characteristics which are based on the test results of small specimens. There are two separate effects under size effect:

1. The greater statistical probability of finding a defect or significant stress raiser in the micro-structure in the larger size.
2. The induced stresses due to restriction of strain in large sizes.(condition of restraint)

The second separate effect is of the utmost importance in the design of structures. Gensamer summed up the difficulties due to size effect by postulating that the size effect is due to inability to scale the fine micro-structure with the specimen size.



### Complex Stress System;-

It should be noted that it is extremely difficult, if not impossible, to separate completely the effects, one from another, that the various factors have upon brittle fracture. When one variable is changed usually another will change, but uncontrollably. An attempt, however, will be made to present the facts as best as they are known, keeping in mind the interdependence, which is unavoidable.

Complex stresses are currently the subject of a great deal of work in which McAdam has been prominent. In a broad way, it is known that biaxial and triaxial stresses will reduce the ductility of metals. The effect on fracture stress is still being argued but it seems that the fracture stress is raised when triaxiality is increased. This fact has been borne out by McAdam and by Sachs. Perhaps the state of affairs can be partially understood when it is realized that conditions of multi-axial stress are obtained by either by notches or by some attempt at direct biaxial stress systems, using clamped down diaphragms or tubes, pulled in tensile machines. Comparisons, particularly in investigating ductility, are often made with normal, un-notched tensile specimens. An interesting postulation made by Jelinek is that there may be two criteria for the fracture of a single metal; maximum shear stress and maximum tensile stress. Fracture would occur when the most severe condition is reached. This is supposed to explain the behavior of cast iron, but then it is to be remembered that Sternberg explained the same baffling behavior of cast iron by a non-linear form of Hooke's law. This is sufficient to show that there

Complex stress system:-

It should be noted that it is extremely difficult, if not impossible, to separate completely the effects, one from another, that the various factors have upon plastic behavior. When one variable is changed usually another will change, but not necessarily. An attempt, however, will be made to present the facts as best as they are known, keeping in mind the interdependence, which is unavoidable.

Complex stresses are commonly the subject of a great deal of work in which Hooke's law has been prominent. In a broad way, it is known that biaxial and triaxial stresses will reduce the ductility of metals. The effect of pressure stress is still being argued but it seems that the pressure stress is related to the ductility in increased. This fact has been borne out by studies and by tests. Perhaps the state of affairs can be partially understood when it is realized that conditions of multi-axial stress are obtained either by stresses or by some attempt at direct biaxial stress systems, using classical stress elements or stress, which in turn also includes compressions, particularly in investigating ductility, and other tests with normal, uniaxial tensile specimens. An interesting presentation made by Johnson is that there may be two criteria for the fracture of a single crystal: maximum shear stress and maximum tensile stress. Fracture would occur when the most severe condition is reached. It is suggested to explain the behavior of cast iron, and that it is to be remembered that Johnson has explained the same brittle behavior of cast iron by a non-linear form of Hooke's law. It is suggested to show that there

is little or no reliable data upon which to base any definite conclusions, other than the apparent reduction of ductility under complex stresses.

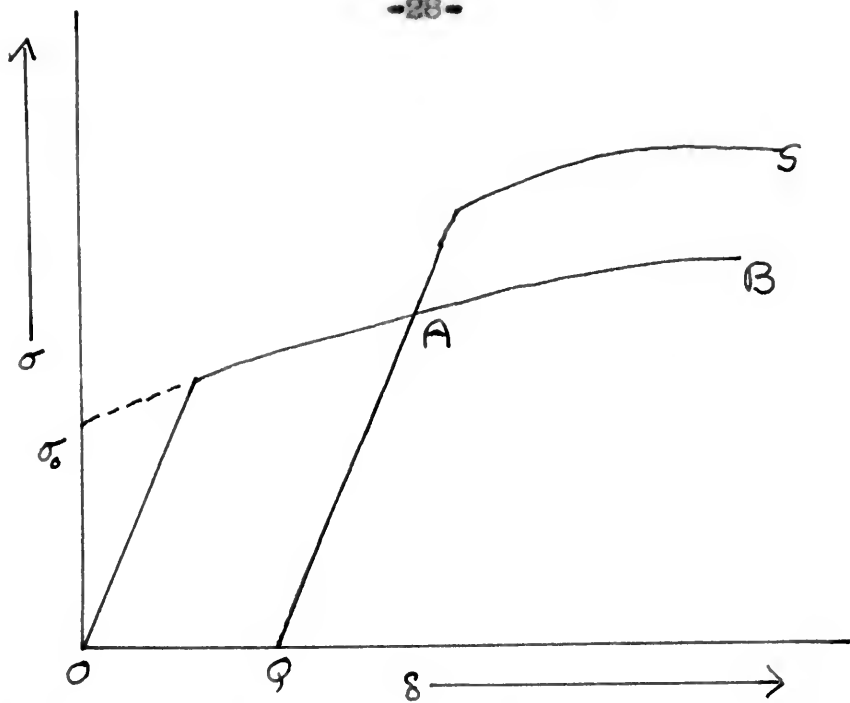
#### Effect of Prior Strain;-

There have been several fairly recent investigations into the effect of prior strain on the fracture strength. Sakharov, in Russia, and Hollomon and Zener, here, have shown that, in the particular case of pearlitic steel, the tensile fracture stress must decrease with the first small amount of deformation. This is shown by the specimen fracturing at a lower stress than the yield stress. In addition to this effect, their work corroborates the early postulation of a fracture curve, as made by Ludwik. The stress required for fracture was shown to increase with increasing strain. Bridgeman applied hydrostatic pressure to a tensile specimen under tension and it was found that the fracture stress was raised. His work tends to substantiate the micro-crack theory of fracture in that there may be a sealing up or welding up of the microcracks under the hydrostatic pressure which would, according to that theory, raise the fracture strength. Saibel has explained the effect of prior strain on fracture from the standpoint of his thermodynamic theory of fracture. His results agree well with the meager experimental data available. The stressing cycle used by Saibel is noted on the next page:-

is little or no reliable data upon which to base any definitive  
conclusions. The data are sparse and not statistically significant.

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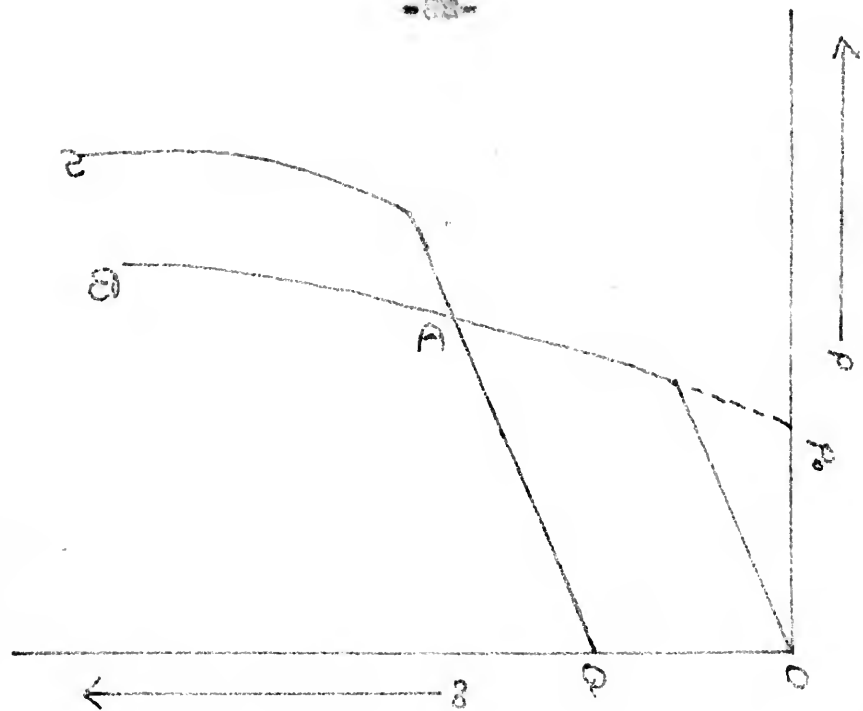


1. metal is pre-strained a given amount at room temperature. (OAQ)
2. the temperature is lowered.
3. the specimen is pulled to fracture. (QARS)

The final status of knowledge to date allows for a prediction of the effect of prior strain by use of the micro-crack theory and energy considerations along with the effects of micro-structure.

#### Effect of Cyclic Loading:-

The question of the effects of cyclic loading or fatigue has been studied from the engineering viewpoint. There is a great deal of data available on fatigue strengths and endurance limits but very little of it delves into the fundamentals of the situation. A little work has been done relative to the dissipation of heat produced as a result of the alternating straining within the metal. This may tie in with the current theories regarding the viscous regions existing at grain boundaries and within slip bands to give a coherent picture. Another unresolved effect is that of prestraining on the fatigue strength. There



1. metal is pre-treated as shown above & heated to 100°C.  
2. the temperature is lowered.  
3. the specimen is cooled to 100°C.

to maintain a not swift pace of adjustment to existing conditions and the effect of prior action by way of the labor market. Every consideration along with the effects of the labor market.

• 1941-1942 1943-1944 1945-1946 1947-1948 1949-1950 1951-1952 1953-1954 1955-1956 1957-1958 1959-1960 1961-1962 1963-1964 1965-1966 1967-1968 1969-1970 1971-1972 1973-1974 1975-1976 1977-1978 1979-1980 1981-1982 1983-1984 1985-1986 1987-1988 1989-1990 1991-1992 1993-1994 1995-1996 1997-1998 1999-2000 2001-2002 2003-2004 2005-2006 2007-2008 2009-2010 2011-2012 2013-2014 2015-2016 2017-2018 2019-2020 2021-2022 2023-2024 2025-2026 2027-2028 2029-2030 2031-2032 2033-2034 2035-2036 2037-2038 2039-2040 2041-2042 2043-2044 2045-2046 2047-2048 2049-2050 2051-2052 2053-2054 2055-2056 2057-2058 2059-2060 2061-2062 2063-2064 2065-2066 2067-2068 2069-2070 2071-2072 2073-2074 2075-2076 2077-2078 2079-2080 2081-2082 2083-2084 2085-2086 2087-2088 2089-2090 2091-2092 2093-2094 2095-2096 2097-2098 2099-2100 2101-2102 2103-2104 2105-2106 2107-2108 2109-2110 2111-2112 2113-2114 2115-2116 2117-2118 2119-2120 2121-2122 2123-2124 2125-2126 2127-2128 2129-2130 2131-2132 2133-2134 2135-2136 2137-2138 2139-2140 2141-2142 2143-2144 2145-2146 2147-2148 2149-2150 2151-2152 2153-2154 2155-2156 2157-2158 2159-2160 2161-2162 2163-2164 2165-2166 2167-2168 2169-2170 2171-2172 2173-2174 2175-2176 2177-2178 2179-2180 2181-2182 2183-2184 2185-2186 2187-2188 2189-2190 2191-2192 2193-2194 2195-2196 2197-2198 2199-2200 2201-2202 2203-2204 2205-2206 2207-2208 2209-2210 2211-2212 2213-2214 2215-2216 2217-2218 2219-2220 2221-2222 2223-2224 2225-2226 2227-2228 2229-2230 2231-2232 2233-2234 2235-2236 2237-2238 2239-2240 2241-2242 2243-2244 2245-2246 2247-2248 2249-2250 2251-2252 2253-2254 2255-2256 2257-2258 2259-2260 2261-2262 2263-2264 2265-2266 2267-2268 2269-2270 2271-2272 2273-2274 2275-2276 2277-2278 2279-2280 2281-2282 2283-2284 2285-2286 2287-2288 2289-2290 2291-2292 2293-2294 2295-2296 2297-2298 2299-2300 2301-2302 2303-2304 2305-2306 2307-2308 2309-2310 2311-2312 2313-2314 2315-2316 2317-2318 2319-2320 2321-2322 2323-2324 2325-2326 2327-2328 2329-2330 2331-2332 2333-2334 2335-2336 2337-2338 2339-2340 2341-2342 2343-2344 2345-2346 2347-2348 2349-2350 2351-2352 2353-2354 2355-2356 2357-2358 2359-2360 2361-2362 2363-2364 2365-2366 2367-2368 2369-2370 2371-2372 2373-2374 2375-2376 2377-2378 2379-2380 2381-2382 2383-2384 2385-2386 2387-2388 2389-2390 2391-2392 2393-2394 2395-2396 2397-2398 2399-2400 2401-2402 2403-2404 2405-2406 2407-2408 2409-2410 2411-2412 2413-2414 2415-2416 2417-2418 2419-2420 2421-2422 2423-2424 2425-2426 2427-2428 2429-2430 2431-2432 2433-2434 2435-2436 2437-2438 2439-2440 2441-2442 2443-2444 2445-2446 2447-2448 2449-2450 2451-2452 2453-2454 2455-2456 2457-2458 2459-2460 2461-2462 2463-2464 2465-2466 2467-2468 2469-2470 2471-2472 2473-2474 2475-2476 2477-2478 2479-2480 2481-2482 2483-2484 2485-2486 2487-2488 2489-2490 2491-2492 2493-2494 2495-2496 2497-2498 2499-2500 2501-2502 2503-2504 2505-2506 2507-2508 2509-2510 2511-2512 2513-2514 2515-2516 2517-2518 2519-2520 2521-2522 2523-2524 2525-2526 2527-2528 2529-2530 2531-2532 2533-2534 2535-2536 2537-2538 2539-2540 2541-2542 2543-2544 2545-2546 2547-2548 2549-2550 2551-2552 2553-2554 2555-2556 2557-2558 2559-2560 2561-2562 2563-2564 2565-2566 2567-2568 2569-2570 2571-2572 2573-2574 2575-2576 2577-2578 2579-2580 2581-2582 2583-2584 2585-2586 2587-2588 2589-2590 2591-2592 2593-2594 2595-2596 2597-2598 2599-2600 2601-2602 2603-2604 2605-2606 2607-2608 2609-2610 2611-2612 2613-2614 2615-2616 2617-2618 2619-2620 2621-2622 2623-2624 2625-2626 2627-2628 2629-2630 2631-2632 2633-2634 2635-2636 2637-2638 2639-2640 2641-2642 2643-2644 2645-2646 2647-2648 2649-2650 2651-2652 2653-2654 2655-2656 2657-2658 2659-2660 2661-2662 2663-2664 2665-2666 2667-2668 2669-2670 2671-2672 2673-2674 2675-2676 2677-2678 2679-2680 2681-2682 2683-2684 2685-2686 2687-2688 2689-2690 2691-2692 2693-2694 2695-2696 2697-2698 2699-2700 2701-2702 2703-2704 2705-2706 2707-2708 2709-2710 2711-2712 2713-2714 2715-2716 2717-2718 2719-2720 2721-2722 2723-2724 2725-2726 2727-2728 2729-2730 2731-2732 2733-2734 2735-2736 2737-2738 2739-2740 2741-2742 2743-2744 2745-2746 2747-2748 2749-2750 2751-2752 2753-2754 2755-2756 2757-2758 27

The question of the effects of cyclic loading on fatigue has been studied from the engineering viewpoint. There is a great deal of data available on fatigue strength and endurance limits for very little of it being in the form of fundamental data. A little work has been done relative to the distinction of test products as a result of the distinction existing with- in the metal. This is in spite of the fact that the same metal and alloy have been used in the same existing in the same metal and alloy in the same way. A great deal of work has been done in this field to give a correct picture of the fatigue strength of a metal in the form of a fatigue strength curve.



are some claims that fatigue is merely strain hardening up to the fracture point. Taken as a whole, it can be seen that there is much work yet to be done on this particular factor. The over-all effect is, however, to reduce the fracture strength as the number of cycles increase

#### Effect of Strain Rate:-

Strain rates, or the dynamic conditions involved, have come in for a great deal of attention. There are two widely divergent strain rates of interest, namely that rate just above being static and rates approaching ballistic velocities. As a side line to the research on strain rates, some interesting work has been done on the strain wave propagation through metals. Briefly, it has been found that the effect of strain rate at normal speeds of testing are not significant and are unimportant. When strain rates approaching ballistic velocities are encountered, that strain rate is very important, since the increase in the flow stress may make it approach the fracture stress and thus cause failure. The elastic waves may also reach fracture magnitudes ahead of the plastic strain waves and thus cause brittleness.

Hollomon and Zener have attempted to derive an interrelation between strain rate and temperature as they affect fracture strength. It is known that decreasing the temperature and raising the strain rate increase the stress required for fracture. This brings up the question of applicability of the mechanical equation of the state of brittle fracture as well as to ductile failure or flow. This particular correlation for the case of brittle fracture is

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#### Effect of Temperature;-

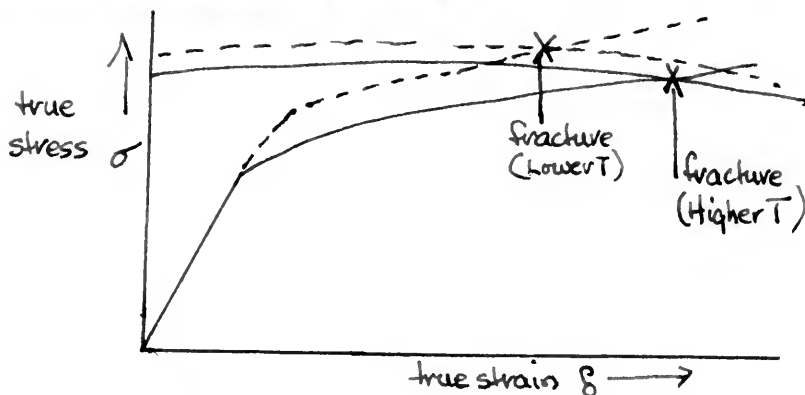
A most important factor regarding fracture strength is the temperature of fracture. It is significant to note that a single metal, such as pearlitic steel, can be made to behave in either a ductile or brittle manner solely by temperature variation. Early work by the Russians attempted to demonstrate that the fracture strength was independent of temperature, but they neglected the important factor of strain rate, which has been discussed above. Present work has shown that fracture strength increases with a decrease in temperature. Departing a moment from purely brittle behavior, it is desired to point out that the flow stress decreases as the temperature is raised until, at the melting point, there is no yielding stress. The flow stress increases with a reduction in temperature but at a more rapid rate than the fracture stress, which allows for fracture at less deformation. This can be shown graphically on a true stress-strain curve. It is interesting to note that the type of fracture changes from a transcrystalline to intercrystalline type as the melting temperature is approached. Hollomon reports a similar behavior at varying strain rates; fast strain rates producing transcrystalline fractures. There is little or no work in the field of combined stresses relative to the effect of temperature on brittle fracture and, in general, more work should be done to try to isolate completely the temperature effects and eliminate the controversies

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beyond a doubt. The following chart shows the over-all effect of temperature as currently accepted:

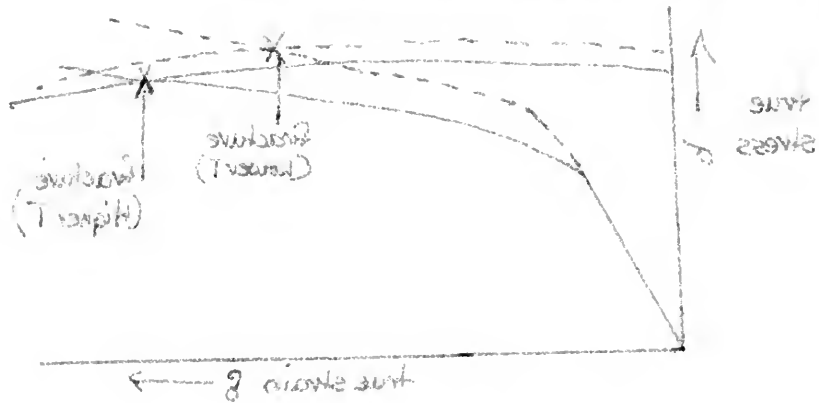


These curves also serve to illustrate how any factor that affects either the flow or fracture curve will affect the ductility and, consequently, the brittle behavior. It is to be remembered that some factors move both curves in the same direction but at different rates. Thus it can be seen that the true Stress-strain curves are very helpful in studying over-all effects, especially for engineering application.

#### Effect of Structure:-

The effect of structure has already been touched upon at several points, mostly during the discussion of statistical analysis. In addition to the carbide particles mentioned, the precipitate formed in age-hardening alloys may have a somewhat similar effect since an embrittling is known to occur in these alloys. A martensitic structure possesses a very high fracture strength, even at low temperatures, when it is tempered and it is generally recognized as being the most desirable structure in steels where low temperature impact properties are required. The effect of alloying

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# Effect of Temperature:-

The effect of temperature has already been discussed upon the behavior of metals, mostly during the discussion of mechanical properties. In addition to the various properties mentioned, the mechanical behavior of a material also may have a somewhat similar effect since an oxidation is known to occur in some alloys. A characteristic structure sometimes a very fine fracture structure, even at low temperatures, may be indicated and it is usually recognized as being the result of oxidation. In some cases low temperature may cause the formation of a brittle phase, the result of alloying

elements should not be overlooked, since it is well known that solid solution hardening has a definite effect in raising the fracture strength. Nickel is somewhat beneficial in aiding low temperature impact strength. Again, more good work is required along these lines to attempt to pin down the influence of structure (and composition) from a fundamental basis.

Restatement;-

This paper has followed the problem of brittle fracture in metals from the logical beginnings in mechanical metallurgy, where the basic engineering mathematical expressions were shown through several controversial subjects (theories) and, finally, the effects of various factors on the fracture strength were briefly reviewed. It depends on one's viewpoint, ie: research or engineering, to determine which part of the discussion is most applicable. That the subject is important is an acknowledged fact and it is all too *apparent* that there is a great deal more work to be done along all phases of this problem. Fortunately the work is being carried forward.

It should also be pointed out that, at this time, it cannot be said which theory is the precisely correct one or what is the correct mechanism of brittle fracture. There is too much conflicting information and it must be remembered that the correct theory must agree *accurately* with observed facts and, furthermore, must be able to predict behavior based on a few experimental



elements are not overlooked, since it is well known that solid solution hardening has a definite effect in raising the fracture strength. It is to be noted that the influence of strain rate is not overlooked, since it is well known that temperature has a marked effect on the strength of materials. Along with these factors, the influence of stress (and composition) must be considered.

References:-

This paper has followed the principles of the fracture in metals from the logical beginning to the mechanical metallurgy, where the basic engineering metallurgical experiments were shown through several experimental subjects (tension, compression, bending, etc.). The effects of various factors on the fracture strength were briefly reviewed. It is hoped that this paper, as a research or engineering, is helpful in determining which part of the discussion is most applicable. The subject is important as an introductory fact and it is all important that there is a great deal more work to be done along all aspects of this problem. Consequently the work in this field is being carried forward.

It should also be pointed out that at this time, it cannot be said which theory is the basically correct one or what is the correct mechanism of brittle fracture. There is too much controversy and it must be recognized that the correct theory will emerge eventually with observed facts and, furthermore, there is still a great deal of work to be done in this field.



calculations. No theory yet presented can fulfill all the requirements. However, each theory and investigation, no matter how small, has added something to the general over-all picture. It is just a matter of time and effort until all the pieces of the puzzle will fall into place. When the theory is complete and known as a "law of brittle fracture", the engineering benefits will be immense and vastly important.

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